REPORT ON A PRELIMINARY

EXAMINATION OF THE SPECTRAL

ENERGY DISTRIBUTION IN THE

JPL SOLAR SIMULATOR

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1. INTRODUCTION

This report summarizes the results obtained during the visit of

the undersigned to the Jet Propulsion Laboratory on 31 January 1963. The

investigation discussed was planned 16 January during a visit to JPL.

Three water-cooled thermopile detectors were employed, one

being the property of JPL and two the property of the Eppley Laboratory

which also supplied the thermopile voltage readout equipment and the

series of broad band filters and windows used. The filter wheel containing

the series of narrow band interference-type filters was made available

by NASA (Goddard Space Flight Center).

Measurements were made in air (total flux and spectrally as

isolated by both sets of filters) and at reduced pressure (total flux

and total ultra-violet and total infra-red regions separately).

The two Eppley working standard thermopiles were calibrated

before and after the experiment, at Newport, in air - no significant

changes in calibration were observed; on return to Newport these thermo-

piles were also calibrated at a reduced pressure of about 10-5 mm Hg, at

the radiant flux densities experienced in the Solar Simulator (i.e. as

used with the UV and IR filters). All calibration values established

were referred to the measured thermopile coolant (water) temperature in

the Space Simulator. There has been no opportunity as yet to verify the

vacuum calibration of the JPL detector but as this is an instrument of recent manufacture with relatively little use, there is no reason to suspect the original Newport calibration: however, inspection of the Eppley records permitted the assigning of a somewhat more refined value in view of the actual operational conditions, during this examination, of ambient water temperature and flux density.*

2. RESULTS

(a) Calibration of detectors

The following is a summary of the calibration program.

	Radiometer	Thermopiles		
Detector No.	No. 4383	5376	2605	4813
Sensitivity 21° C				
Air mv/mw cm^{-2}	0.253	0.129	0.0228	0.00575
Vacuum	0.275	0.417	0.0607	----

Remarks

1. The air calibration of detector No. 4383 refers to the circuit with the pressure thermistor (i.e. similar to the vacuum calibration) and was obtained through a comparison on 31 January with thermopile No. 5376 at a radiant flux density of 122 mw cm^{-2}. The vacuum calibration of No. 4383 is the original Newport one with slight adjustment for the specific exposure conditions.

2. The air calibrations of detectors Nos. 5376 and 2605 refer to a flux density of 122 mw cm^{-2} (No. 5376 employed also with the narrow and broad band pass filters has a radiation intensity-thermopile emf

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* The radiometer was received from JPL after this report was prepared and its calibration verified to within ± 1 per cent.

relationship which is linear to within ± 1 per cent over the entire range of flux density to which it was exposed in these tests). The vacuum calibrations of detectors Nos. 5376 and 2605 refer, respectively, to flux densities of the order of 10 and 50 per cent of the total unfiltered Simulator flux measured in vacuum on 31 January (i.e.) 139 mw cm^{-2}). Both series are Newport based.

3. Thermopile No. 4813 belongs to JPL but was not employed in the tests reported on here. It was calibrated, in air, by comparison with thermopile No. 5376 on 31 January at a flux density of 122 mw cm^{-2}. The result is included for future convenience.

4. Radiometer No. 4383 is a 180° aperture, pressure compensated detector (15-junction bismuth-silver element plus a bead-type sensing thermistor) to which JPL have fitted a water-cooled tube restricting the aperture to about 30° (estimated). Thermopile No. 5376 is an 8-junction bismuth-silver unit and thermopile No. 2605 is a 4-junction copper-constantan unit (in both instances, the aperture angle is approximately 70°). Thermopile No. 4813 is a single-junction manganin-constantan high-radiation intensity unit (aperture angle approximately 50°).

(b) Instrumentation

The measurements of total flux with radiometer No. 4383 were obtained with the aid of a Minneapolis-Honeywell (Brown) recording potentiometer with full-scale deflection (100 divs.) set at 50 millivolts. This arrangement provided the record of total flux under vacuum conditions. The measurements of total and spectral flux (narrow and broad band filters) in air and UV flux in vacuum were

obtained with thermopile No. 5376 connected either to a Leeds and

Northrup model H recording potentiometer (full-scale deflection

100 divs. set at 10 millivolts) or to a Leeds and Northrup D. C.

thermocouple indicating amplifier, as dictated by the experiment:

an Eppley precision microvolt-millivolt reference source (accuracy

better than 0.1 per cent) was employed to check these emf readout

systems. The second thermopile (No. 2605) was used for additional

measurements of the total flux in air and also for the record of IR

flux in vacuum. Through a thermal free switching arrangement, the

signal from this detector was likewise displayed on the L. and N.

potentiometer. Thermopiles Nos. 5376 and 2605 provided the reference

of total flux in air.

Details of the window materials and broad band filters employed

are as follows:

A (1) crystal quartz: uniform transmittance 250-3000mu

  (2) pyrex: center of lower cutoff 295 mu, transmission in general

         similar to quartz

  (3) Schott
    GG 14: center of lower cutoff 502 mu, filter factor 1.10

  (4) Schott
    OG 1:   "   "   "   "   535 "   "   "   1.10

  (5) Schott
    RG 2:   "   "   "   "   636 "   "   "   1.10

  (6) Schott
    RG 8:   "   "   "   "   697 "   "   "   1.10

  (7) Schott
    UG 11: band pass 265-385 mu, maximum transmittance 0.68 at

335 mu (N.B. this filter was employed to isolate the total UV emission of the source; the filter factor is approximately 2.35 for this type of emission)

The corresponding information regarding the narrow band pass filters is

	Filter limits mu	Effective Hg isolation mu	Mean filter transmittance for Hg isolation	Filter factor
B (1)	240-310	260-305	0.09	11.1
(2)	275-315	275-310	0.11	9.1
(3)	305-335	310-320	0.14	7.2
(4)	325-355	330-340	0.20	5.0
(5)	335-390	360-370	0.26	3.8
(6)	385-420	400-410	0.34	2.9
(7)	415-460	430-440	0.50	2.0
(8)	515-585	540-550	0.63	1.6
(9)	565-610	570-585	0.47	2.15
(10)	620-810	650-750	0.59	1.7
(11)	770-1250	825-1125	0.60	1.65
(12)	1000-1650	1075-1525	0.63	1.6

The A windows and filters were either mounted separately or unmounted; the B filters were mounted in a filter wheel which was attached to the thermopile in operation.

(c) Source

The energy source was the emission, in air and vacuum, by a

series of 127 2.5 KVA Hanovia mercury-xenon high-pressure short arcs
operated close to this nominal input power level. Under atmospheric
conditions in the Simulator, the source was operated continuously for
about one hour, for stability reasons, before radiant flux measurements
were made. On completion of this part of the program, the lamps were
switched off and the Simulator evacuated to a pressure of approximately
10-5 mm Hg and the walls cooled to a fairly uniform temperature of
$-260°$ F*. The source was then turned on (about 2 1/2 hours after the
commencement of chamber evacuation) and a series of simultaneous total,
UV and IR flux measurements made over the period of +14 to +30 minutes.
At about 5 minutes after start up, three lamp power supplies failed;
three replacement lamp units were immediately switched in. It is con-
sidered that this variation of three lamps out of a total of 127 did not
appreciably affect the integrated total and spectral fluxes. The source
was operated at the same input power level as employed in the first part
of the experiment.

During the measurement program, in air, the relative humidity
in the vicinity of the Simulator (door open to the environment) was
observed to be 65 per cent: as the temperature inside the Simulator was
estimated at $90°$ F (approximately $30°$C), as compared with $70°$ F ($20°$ C)
externally, the absolute vapor pressure of the air in the chamber, prior
to evacuation, was of the order of 16.5 mb. Visually, it was observed
that the air in the chamber and in its close proximity, at this time,
was distinctly hazy (smoky) indicating the presence of significant
solid particulate matter. The coefficient of radiant energy extinction

* approximately $-160°$ C

by haze does not follow the same law as the extinction by clean dry air.
In the natural condition, the attenuation of the direct solar radiation
on account of scattering by the dust and haze (aerosol) content of the
atmosphere may be reflected, on a relative scale, through derivation of
the Ångström turbidity coefficient B. At present, there is no standard
manner in which such a comparative scale may be established for artificial
sources operated at distances of the order of 50-100 feet from the location
of the radiant energy sensing equipment. It was estimated (by JPL) that
the general ozone concentration generated during the experiment was about
$15/10^8$ (presumably by volume). With these facts in mind, there is no
question that, on evacuation of the Simulator, on this occasion where the
contained (contaminated) air probably represented a near maximum total
turbidity condition for this environment as exercised through selective
scattering and absorption by particulate matter and by absorption by water
vapor and ozone (and to a lesser extent by carbon dioxide), a measurable
increase should be experienced in the ultra-violet region (and probably
also in the shorter visible wavelengths) and a marked increase in the
infra-red region. The validity of this argument is illustrated in the
tabular material presented in this Report.

(d) Test procedure

With the A-type filters, in air, etc, one complete set of meas-
urements was made, in air, at one location of the test plane: the scheme
was thermopile plus quartz; plus pyrex; plus quartz + GG 14, + OG1, + RG 8,
+ UG 11; plus quartz. A measurement was also made with the thermopile
completely unscreened. Duplicate measurements of total flux were obtained,
as a precautionary measure. During the vacuum portion of the test, the

measurements were restricted to total flux (one series of readings) and
thermopile plus quartz + UG 11 and second thermopile plus quartz + RG 8.

The B-type filters could only be exposed (over the same thermo-
pile as employed for the A-typs filter measurements), in air, as this
operation involved manual adjustment of the filter wheel: one set of
readings was obtained.

(e) Data presentation

The basic results are presented in the following Tables I-VI.
Tables I, III and V give the basic measurements; Tables II, IV and VI
give the energy distributions in the various spectral regions.

TABLE I Total flux and broad band data (relative units: mv) in air

Quartz	Pyrex	Q +GG 14	Q +OG 1	Q +RG 2	Q +RG 8	Q +UG 11
15.7	15.4	11.5	11.3	9.1	8.6	0.90

TABLE II Spectral energy distribution (per cent) in air

	Total	<295 mu	<385 mu	385–502 mu	502–535 mu	535–636 mu	636–697 mu	>697 mu
mw cm^{-2}	122	2	13	6	2	15	4	60
w ft^{-2}	113							

N.B. 1. Energy conversion factor: 7.20 w ft^{-2} per mv x filter factor.

2. The result of the test made by exposing the thermopile without any
window in position indicated an increase of 8 per cent over the corr-
esponding value with the quartz window in position: as the general
transmittance of this specimen of quartz is 0.92, the conclusion is
that there is no significant source emission of wavelength exceeding
3 ", at least as measured in the location selected by JPL.

TABLE III Narrow band data (relative units: mv) in air

B 1	2	3	4	5	6	7	8	9	10	11	12	Total
37	69	35	32	255	164	426	778	818	576	2220	2240	15650

TABLE IV Spectral energy distribution in narrow bands (per cent) in air

B 1	2	3	4	5	6	7	8	9	10	11	·12
3	4	3	1	6	3	5	8	11	6	24	23

Summary - air

	Broad band %	Narrow band %
UV (i.e. $<$ 380 mu)	12	13 (mean B 1 and 2 plus 3,4 and 5)
VIS (380-750 mu)	31	33 (B 6,7,8, 9 and 10)
NIR ($>$750 mu)	57	47+(B 11 and 12 plus IR not Measured)

N.B. Broad band values for UV and NIR are adjusted slightly to coincide with the adopted wavelength limits.

TABLE V Total flux and broad band data (relative units: mv) in vacuum

Total (no window)	Q +UG 11	Q +RG 8
38.2	3.20	4.50

TABLE VI Spectral energy distribution (per cent) in vacuum

	Total	$<$ 385 mu	$>$697 mu
mw cm^{-2}	139	13	59
w ft^{-2}	129		

N.B. 1. Energy conversion factors: total 3.38 w ft^{-2} per mv; UV 2.23 w ft^{-2} per mv x filter factor; IR 15.3 w ft^{-2} per mv x filter factor.

2. In the case of the ultra-violet isolating filter, there was no significant secondary transmission; appropriate correction was applied for filter emission (through observation of the signal immediately the lamp source was switched off). In the case of the infra-red isolating filter, the constancy of measurement over the 15-minute period was remarkable (viz. ± 0.5 per cent); there were no significant filter emission effects.

Summary - vacuum

	Broad band %
UV (i.e. $<$380 mu)	12
VIS (i.e. 380-750 mu)	32
NIR (i.e. $>$750 mu)	56

N.B. See remark under corresponding summary statement for air measurements.

3. CONCLUSIONS

(a) There is no significant change in the relative energy distributed between the three principal spectral regions.

(b) This distribution (viz. 12% UV, 32% VIS and 56 % NIR) may be compared with that derived by Johnson (J. Meteor., 11, 431-439, 1954) for solar spectral irradiance at mean zero air mass, viz. 7.5% UV, 46% VIS and 46.5% NIR. In more detail, this comparison may be given as follows (band pass filter values for Hg source, air path):

	Spectral distribution (per cent)						
mu	$<$295	$<$385	385–502	502–535	535–636	636–697	$>$697
Sun	1	8	16	4	13	7	52
Hg (broad band filters)	2	13	6	2	15	4	60

mu	240-310	275-315	305-335	325-355	335-390	385-420	415-460	515-585	565-610	620-810	770-1250	1000-1650
Sun	1.5	1.5	2	2.5	3	4	6.5	9.5	6	19	26	19
Hg (narrow band filters)	3	4	3	1	6	3	5	8	11	6	24+	23+

It was considered more appropriate, in this comparison of the energy emission of what is essentially a continuous source with that of a discontinuous one, to tabulate the solar values for the whole of the spectral regions isolated by the filters (i.e. as encompassed by the zero transmission filter limits) rather than those values for the reduced portions of these filter band passes which essentially isolate the Hg emission. The resulting agreement is surprisingly good as a first approximation to the sun's extra-terrestrial emission (especially in view of the present uncertainty of the spectral distribution in certain solar wavelength regions as evidenced by the studies of Nicolet - see "Archiv Meteor., Geophysik, Bioklim.", A, 3, 209-219, 1951 - versus Johnson), but significant improvement could still be effected through reduction in the magnitude of the UV and IR components.

(c) On evacuation of the Simulator the increase in (absolute) total flux density appeared to be 14 per cent. The UV increase contributed about 2 per cent and the IR increase about 8 per cent. The remaining 4 percent could be accounted for, totally or partially, as follows: inequality of source output during the two sets of radiometric measurements, slight inconsistencies between the several detector calibrations, in air and vacuum (perhaps 1-2 per cent), or a real increase in the visible region contribution (not measured in vacuum), especially in the shorter wavelengths as a result of reduced particle scattering. For more normal (perhaps controlled) conditions of the Pasadena Simulator atmosphere, this total increase in flux density might be estimated

at 5-10 per cent.

4. RECOMMENDATIONS

The experiment should be repeated with emphasis on the following aspects:

(a) Narrow band and broad band filter examination of vacuum as well as air conditions of detector exposure (this will entail automatic manipulation of the filter wheel or wheels and automatic exposing and shuttering of the detectors);

(b) Extension of the spectral examination to include a more detailed investigation with a suitable monochromator (this would also enable the narrow band pass filter factors to be refined for this particular source as modified by the optics involved);

(c) Auxiliary monitoring of the output source power (in the instance of air versus vacuum Simulator conditions) with the aid of a stable sealed detector (whose response would be independent of ambient pressure and restricted, with a filter transmitting only in the 600-700 mu region, to a spectral band of minimum scattering and absorbing atmospheric attenuation).

5. ACKNOWLEDGEMENT

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